Sandia National Laboratories
University Alliance Design Competition
MEMS Educational Design Category

MEMS MicroBarbershop

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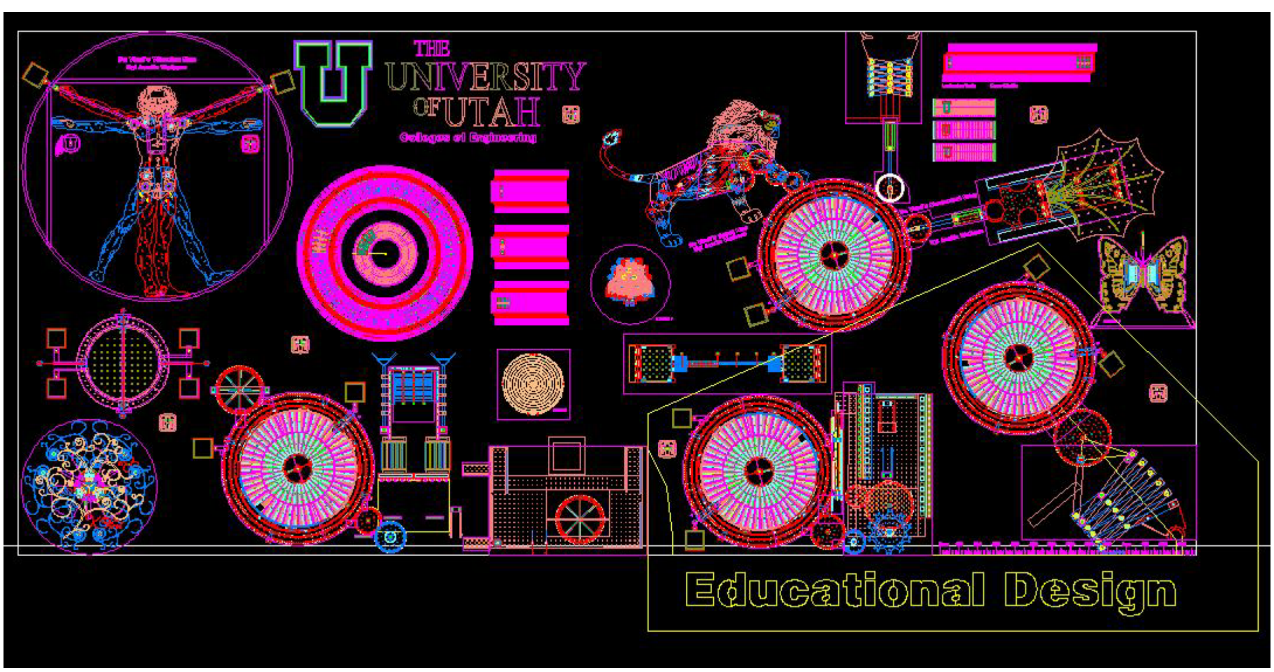
A MEMS design using the Sandia National Laboratories SUMMiT-V^{TM} design tools and process architecture, especially for the purpose of demonstrating to grade K-12 kids how cool it is to design machines at a scale small enough to manipulate individual human hairs.



Abstract

We have invented an interactive, educational MEMS MicroBarbershop, designed to effectively communicate the scale of MEMS devices and convey a sense of utility in manipulating micro-sized objects. The surface-micromachined MicroBarbershop system consists of a microgripper that reaches off the chip to grasp a human hair and holds it in front of an off-chip deployed micro-buzzsaw to be cut. Both devices are driven by a TRA [1]. Our design will be actuated using the Texas Tech outreach MEMS test system [2] under a video-enabled optical microscope station while being observed by a group of students on a large video monitor, visually engaging them as it moves and cuts a human hair. We have also included a moveable micromirror and an off-chip micro hair dryer to complete the playful notion of a barbershop in the context of helping create and maintain K-12 student interest.

Introduction

Our familiarity with our own hair makes comparing the size of a single human hair to MEMS an effective and popular way [3] to demonstrate the relative scale of engineered microdevices. Our entry into the Sandia MEMS Educational Design category demonstrates micromachines manipulating and interacting with something that everyone can relate to. This MicroBarbershop is intended specifically to teach young students about both the size and capabilities of microelectromechanical devices and systems, comprising:

- Microgripper for holding a single human hair and moving it into position to be cut, demonstrating principles of microelectromechanical manipulation and leading to discussions of applications of MEMS in microrobotics.
- Microsaw for cutting the hair, demonstrating microgears and the interaction of MEMS with the human body and leading to teaching opportunities about MEMS material properties as well as their applications in microsurgery.
- Micromirror for examining the quality of the cut, demonstrating the interaction of light with MEMS and leading to discussions about the optomechanical properties of MEMS and their applications in fast telecommunications and projection systems.
- Microhairdryer for blowing heated air past the hair, illustrating how MEMS can produce heat and manipulate air using a resistive microheater and microfan, and leading to discussions about MEMS applications in ink jet printers and gas and air flow sensors.

Because the rules of the competition state that we must enter only one device for judging, this white paper describes the theory, operation, and educational utility of the hair cutting tool of the micro salon, namely the microgripper and microsaw. Lesson plan ideas and activities that teach students about the MicroBarbershop devices are also outlined.

Device Description

Overview

The hair cutting tool consists of two main components: a microgripper and a microsaw. The microgripper extends over the end of the chip, closes around a hair, and moves it into position in front of the microsaw. The microsaw also extends over the edge of the chip, begins rotating, and makes a cut into the hair. When the microgrippers retract, they unclasp the cut hair.

Microgripper Description

The microgrippers consist of a pair of circular tweezers ends attached to an array of scissor hinge linkages that translate small linear motion into a large extension. The arms of the scissor hinges are alternately constructed in layers MMPOLY3 and MMPOLY4. Pins are used at both ends and in the middle to allow each linkage to rotate freely while pushing the next linkage forward as shown in Figure B1 and B2. Because the middle pin is offset from the center, the motion of the tweezers ends extend outward in a curved path instead of linearly, as shown in Figure B3.

The scissor hinge linkage assembly, commonly referred to as "lazy tongs," is attached to a crank rocker mechanism that utilizes a gear, a pin hinge, and anchored pins to change the circular motion of the gear into an oscillating semicircular motion. One end of the scissor hinge assembly is connected and utilizes the semicircular motion to push the rest of the hinge linkages forward. The gear that is used to provide the circular motion of the crank rocker is driven by a torsional ratcheting actuator (TRA), a standard component in the Sandia SUMMiT V^{TM} component library. The speed that the microgripper extends varies according to the frequency with which the TRA is driven. The microgripper holds its position when the power to the TRA is turned off. The microgripper extends to the limit of its travel and then retracts because the crank rocker reverses its direction when the gear rotates 180 degrees causing the arm attached to the gear to reach the extent of its travel and return to its original position.

Microsaw Description

The microsaw has a thin polysilicon cutting blade on layer MMPOLY3 that hangs down from the MMPOLY4 polysilicon layer above it. The upper MMPOLY4 layer is attached to a slider on both sides, making it possible to move the blade out over the edge of the chip. The cutting blade has gear teeth that connect to a gear train on a lower MMPOLY2 polysilicon layer. The gear train is connected to the upper MMPOLY4 layer and suspended off the substrate, allowing the whole system to slide together.

In its initial as-fabricated position, a torsional ratcheting actuator is coupled to a linear rack, which is connected to the MMPOLY4 microsaw slider. As the TRA rotates, the linear rack slides the microsaw assembly towards the edge of the chip until the saw blade extends off the chip. At the end of its travel, the slider latches into place, and the assembly stops moving off the chip because the teeth on the linear rack end. Once the slider is in the off-chip position, the teeth of the gear train engage with the TRA. Operating the TRA causes the microsaw to rotate. The rotational speed of the saw varies depending on the frequency used to drive the TRA and is detailed in Table A2.

Device Operation, Theory, Modeling, Uniqueness, and Strengths

Operation

- Seek voluntary donation of a hair sample.
- Grab hair with hand-held fine tweezers.
- Apply slow pulsing voltage (30 V, ~5 Hz) to actuate TRA#1 which pushes out lazy tong grippers.
- Carefully manipulate hair under microscope so it is directly in front of microgrippers. Continue to slowly actuate TRA #1 to catch hair with microgripper.
- Stop TRA #1 when hair is grasped by microgripper.
- Actuate TRA #2 (30 V) to slide microsaw off chip and engage gear train with TRA.
- Start microsaw rotation by applying rapid pulses to TRA#2 (30V, 1 kHz).
- Very slowly bring hair directly in front of microsaw by applying single pulses to TRA#1 and cut into the hair.
- Retract gripper and grab hair with handheld tweezers. Place hair under high magnification microscope or SEM to display cut.

MicroBarbershop Chip Design Considerations, Theory, and Modeling

The purpose of the microgripper is to extend off the chip, grab a hair, and hold it in front of the saw. The tweezer ends must start far enough apart and be shaped to be able to effectively grasp a human hair. A typical human hair diameter averages about 55 µm and so the microgripper ends are fabricated with a 60 µm internal radius to be able to grasp the hair [4]. The circular tweezer ends of the microgripper are fabricated 65 µm apart. As the lazy tong extends off the chip it slowly pushes the microgripper ends together and once it grasps a hair the lazy tong continues to apply pressure, holding the gripper ends together and the hair firmly in place.

The curved lazy tong design uses a Grashof class III, four-bar linkage to multiply the input displacement of the first leg, as described in Appendix A. The arc length of the outer arm of the lazy tong is calculated to be 1.67 mm for an input arc length of the rocker arm of 265 µm and a total linear crank displacement of 168 µm. A mechanical model and animation of the curved lazy tong was produced using SolidWorks 2009 and is shown in Figures C1, C2, and C3. The microsaw is located so that the center of the microgripper arrives precisely in front of the saw blade and makes a 15 µm deep cut into the hair.

The object of the microsaw is to extend off the chip and cut into the hair. The blade must be hard enough to cut the hair and be rotating quickly. The material hardness of silicon is compared to that of a human hair in Table A1 [5]. The hardness of silicon is approximately 33 times that of a typical human hair. The TRA is connected to the microsaw via a gear train with a gear ratio of .045, producing an increase of rotational velocity of 22.2 times that of the TRA. If the TRA is operated at its resonant frequency of 5 kHz, the microsaw will rotate at 27,000 rpm, as shown in Table A2.

Solutions to Possible Design Problems

A four µm high ridge of sandwiched polysilicon layers is fabricated on the perimeter of each chip as part of the scribe lane delineation. The devices that extend off the chip must clear that layer, be flexible enough to bend over it, or the ridge must be removed. In our case we are relying on the FIB milling technique if ridge removal is necessary.

The TRA must couple with both the lazy tongs and the microsaw to automatically slide them off the chip. If this actuation fails, the devices may still be manually moved into position with a micromanipulator probe tip.

If the lazy tong microgrippers do not hold the hair in the correct position in front of the microsaw because of machine tolerance in the pin joints or an error in the design a second chip will be lined up directly across from the microsaw and a linear lazy tongs micro grabber will be used to hold the hair in the correct cutting position.

Uniqueness

The microgripper portion of the MicroBarbershop chip incorporates two advanced mechanical mechanisms, a crank rocker and a scissor hinge assembly to translate the rotational motion of the TRA into a very large (> 1.5 mm) curved displacement of the microgripper. The microgrippers not only extend off-chip but also retract back into their original on-chip position. Displacements of this magnitude and micromechanisms of such high complexity distinguish the microgripper.

The microsaw device consists of gears that hang down from MMPOLY4 and slide outward to engage with stationary gears anchored to the substrate. The saw blade extends over the edge of the chip to perform a cut. The hanging, moveable gears and the off-chip cutting operation of the microsaw are enabled by a unique design as shown in Figures B4, B5 and B6.

SUMMiT-V™ Specific Strengths

The design and operation of the microgripper and its subcomponents is enabled by SUMMiT-V™ technology. Specifically, the crank rocker utilizes a pin joint cut and a component library-standard hub to connect the arm to the gear and allow the gear to rotate while pushing the arm forward. The connection between the arm and the scissor hinge mechanism is also facilitated by a vertical pin that allows the arm to push the mechanism outward while simultaneously rotating.

The microsaw requires SUMMiT-V™'s four discrete mechanical layers to be able to slide off the chip, cut with a saw blade, and still be connected to and driven by an on-chip gear train with teeth underneath the saw blade. It is also of great importance to access the fully planarized SUMMiT-

V™ process for these rotating devices, because layer topography would prevent the intended motion.

The standard component library provides the TRA used to drive the whole system, which is a highly reliable, easy-to-use rotational comb drive actuator. The gear maker feature allows seamless integration of the teeth under the microsaw with the parts in the gear train, which engage effortlessly with the teeth on the TRA.

Educational Value, Audience, and Lesson Plan

Educational Value

Besides utilizing the size of a human hair to illuminate the scale of MEMS devices, the MicroBarbershop chip effectively demonstrates other micro-scale phenomena.

For example:

- Material properties of silicon are displayed by the hardness of the microsaw, the flexibility of the microgripper and the elasticity of the center springs in the TRA.
- Conversion of rotational motion to linear motion is shown as the TRA pushes the microsaw off the edge of the chip. Small-displacement curved motion is translated into large-displacement curved motion as the end of the crank rocker pushes and pulls the end of one of the arms of the lazy tongs.
- Many other mechanical mechanisms are also illustrated including hinges in the lazy tongs, ratchets in the TRA, and gear trains that increase the rpm of the TRA to drive the microsaw at high rpm. Window cut-outs and large holes in several gears allow observation of rotation and gear teeth meshing.
- Electrostatic force and actuation are demonstrated by the TRA and its comb-drive fingers.

Target Audience

This MEMS educational chip is primarily directed towards middle and high school students with the aim of awakening their interest in science and microtechnology fields. The intended outcome of such a demonstration is "Its SOOO cool to be an engineer!" The visual display of several MEMS components working together to perform microrobotic handling of a human hair may also have broader appeal to younger students perhaps as well as serious beauty college students!

Lesson Plan Ideas (so the students can tell Mom they got "a" hair… …cut)

<u>Activity 1: Lazy Tong Mechanical Mechanism Construction</u>

- Supplies needed: scissors, thick card stock paper, ruler, brads for pins
- Give students a specification for how far a lazy tong device needs to extend (e.g. 12"). Have them perform the calculations to determine length and number of arms needed to meet spec.

- The lazy tong equation for straight extension is found in Appendix A.
- Make a lazy tong device with paper and brads as shown in Figure D1 and D2 using student's calculated dimensions.
- Actuate lazy tongs manually, holding down on one end point for an anchor.
- Measure actual total displacement and compare with student's calculations.

<u>Activity 2: Hair Study and MEMS Size Comparison</u>

- Supplies needed: microscope, tape, glass slide, various hair samples, penny, standard straight pin, MicroBarbershop educational chip, microscope image capture, and measurement capability, if available.
- Hair Study
  - Request a hair sample from several students, or have them take a nose hair from their teacher.
  - Tape hairs closely spaced to glass slide.
  - Place under microscope.
  - Compare diameters of each hair.
  - Measure diameters if microscope is equipped with measurement instrumentation. If not, estimate relative hair diameter differences.
  - Log data from measurements and graph hair diameters.
- MEMS Size Comparison
  - Tape pin and hair on penny.
  - Place under microscope and observe relative sizes.
  - If microscope is equipped with measurement instrumentation, measure diameters of hair, pin head, penny, and one gear on the educational chip. Otherwise use the on-chip micro-ruler provided.
  - Log measurement data and graph diameters of measured objects from small to large.

<u>Activity 3: Electrostatic Demonstration</u>

- Supplies needed: balloon, MicroBarbershop educational chip, probe station with microscope, camera, and large display, controllable power supply capable of producing 30 V pulses, two micromanipulator probes to connect power to chip bond pads. (Supplied with the TTU outreach MEMS test station).
- Electrostatic Demonstration
  - Blow up and tie balloon.
  - Have a student rub the balloon on their head then move balloon away from hair.
  - Observe hair stand up and be attracted to the balloon. Teach how rubbing balloon and hair transfers charge, creating oppositely charged surfaces. Explain how oppositely charged surfaces attract and how that can create a force capable of moving small light objects such as a human hair or a MEMS comb drive.

Ask students to determine what happens to the force as the balloon comes closer or goes farther away from the hair.

- Connect TRA to microprobes on probe station and apply voltage.
- Apply voltage pulses from 5 to 30 V in 5 V increments and observe the TRA's internal comb drive, ratchet, and gear teeth motion at each voltage level.

Activity 4: MEMS Demonstration

- Supplies needed: MicroBarbershop educational chip wire bonded and packaged, TTU outreach MEMS test station, scissors.
- Show students the unmagnified actual size of MicroBarbershop Educational chip.
- Place chip under microscope and show students the MEMS devices that will be used to manipulate the hair. Describe how each component operates.
- Follow operation procedure as described in device operation section of white paper.
- Examine the cut hair under the microscope, take pictures and measure cut depth and width using the on-chip micro-ruler as a reference.
- Tell the student that donated the hair that they owe you $10 for the hair cut.

APPENDIX A: Calculations

Microsaw Cutting Ability

It is important to determine that the hardness of silicon is higher than the human hair in order to make a cut into the hair with our microsaw device. Table A1 illustrates the relative hardness of several materials, indicating that silicon is approximately 33 times harder than human hair. This shows that the Microsaw will be able to cut through the human hair without damaging the Microsaw. Fiber issues and tangling are yet to be determined.

Table A1. Comparison of Material Hardness Values [4, 5, 6]

Material	Hardness (GPa)	Mohs Hardness
Human Hair	.25	2.5-3
Silicon	8.3	6-7
Steel (max. strength)	14.7	7.5-8
Silicon Carbide	24.3	9
Diamond	68.7	10

Gear Ratio Equations

Gear trains consist of gears that are meshed together with different amount of teeth on each gear to obtain a new angular velocity output. The following equation shows how to obtain the gear ratio [7];

$$m_v = \pm \frac{N_{driven}}{N_{driving}} \tag{1}$$

Where m_v is the velocity ratio and N_{driven} is the combination of all driven gear teeth and $N_{driving}$ is the combination of all driving gear teeth.

The gear ratio works by applying a certain angular velocity to the first input gear and as the gears are turned, the final output gear will obtain the m_v.

Microsaw Gear Ratio:

It is important to determine the gear ratio for the microsaw so that it will achieve the high angular velocity required to be able to cut through the hair.

There are six gears including the TRA and the compound gear inside the microsaw in the gear train. The follow equation solves for the gear ratio between the TRA and the microsaw using equation (1) and gear teeth from the AutoCAD design.

$N_{TRA} = 200,\ N_{gear\,1} = 45,\ N_{gear\,2} = 30,\ N_{gear\,3} = 27,\ N_{gear\,4} = 63,\ N_{microsaw} = 9$

$m_{microsaw} = \frac{N_{microsaw}}{N_{TRA}} = \left(-\frac{45}{200}\right)\left(-\frac{30}{45}\right)\left(-\frac{27}{30}\right)\left(-\frac{63}{27}\right)\left(-\frac{9}{63}\right) = \left(-\frac{9}{200}\right) = 0.045$

For every rotation of the TRA, the microsaw will rotate 22.2 times and the angular velocity of the microsaw will be 22.2 times the angular velocity of the TRA.

Table A2. Microsaw RPM Calculations

TRA Pulse Frequency (kHz)	TRA rpm	Microsaw rpm
.5	2.1	2772
1	4.2	5544
5	21	27720

Lazy Tong Calculations, Straight Extension

The straight lazy tong, functions similar to a pantograph. The total displacement of the lazy tong scissor linkages may be calculated using the equation $x = 2Ns \sin \theta$, where s is the length of a link in lazy tongs of N sections, x is the distance of extension, and θ is the angle shown in the Figure A1.

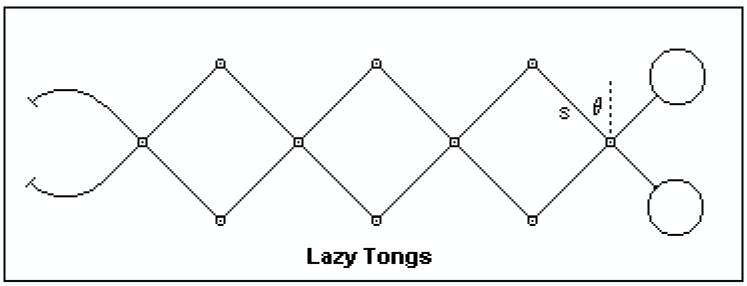


Figure A1. Straight Lazy Tong with length of s [8].

Lazy Tong Calculations, Curved Extension

The curved lazy tong functions as a Grashof four bar linkage. There are several special cases of Grashof four bar linkages. Below shows the Grashof condition equation;

$$S + L \cong P + Q \tag{2}$$

where S is the length of the shortest link, L is the length of the longest link and P is the length of one remaining link and Q is the length of the other remaining link, as shown in Figure A2. Depending on which side of the equation is greater than the other side of the equation, the Grashof Class can be determined. This equation is used to find the Grashof condition which determines the Class of the four bar linkage. It allows for the understanding of the rotation behavior of the linkage.

The curved lazy tong is a Class III four bar linkage since the shortest length is 175 µm and the longest length is 275µm and the remaining linkages are 175 and 275 µm respectively. This creates a double-rocker type of fourbar linkage when using equation (2). Since the four bar linkages are in series, it creates the curvature in the device since each linkage induces the next linkage in series to rotate the same direction.

Each of the beams in the curved lazy tong is 35 µm wide and 500µm long with a spacing of 450 µm between the centers of the outside pin joints.

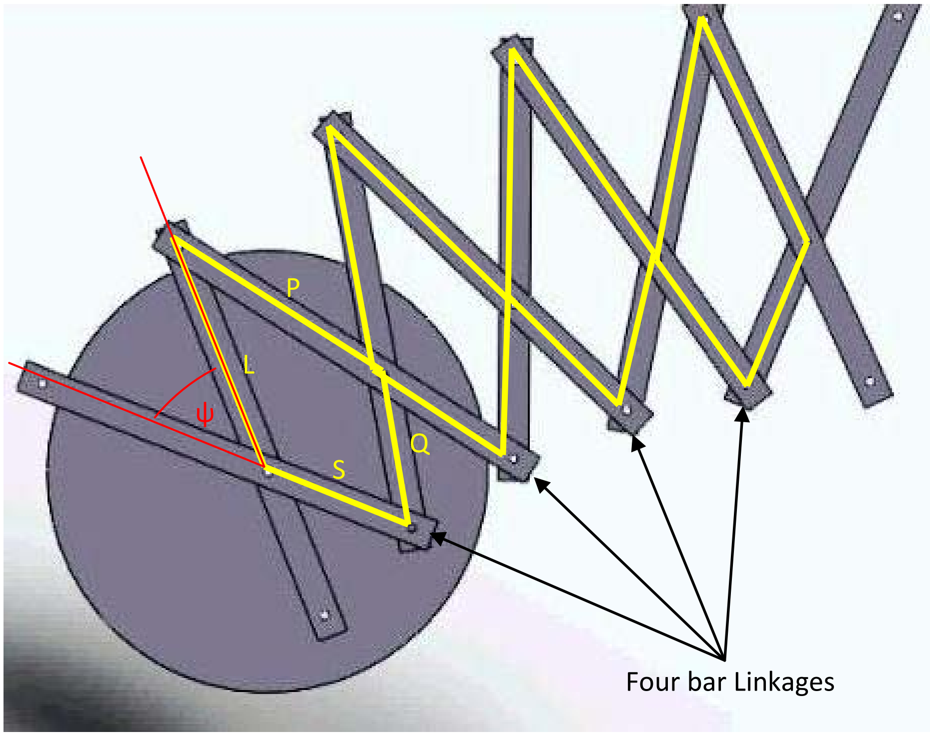


Figure A2. Indicators of four bar links in the Curved Lazy Tong.

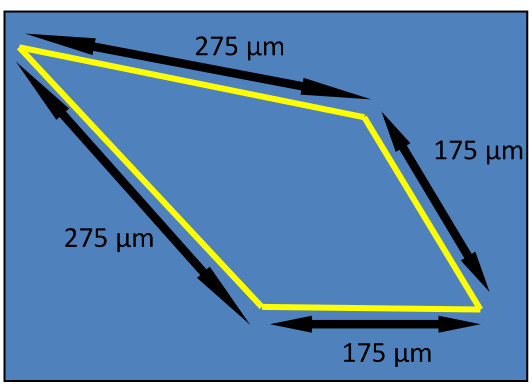


Figure A3. Lengths for each link of the four bar linkage.

The following equations were provided by Dr. K. L. DeVries of the University of Utah Mechanical Engineering department, and they help determine the motion of point *O* and its rotational displacement shown in Figures A4 and A5.

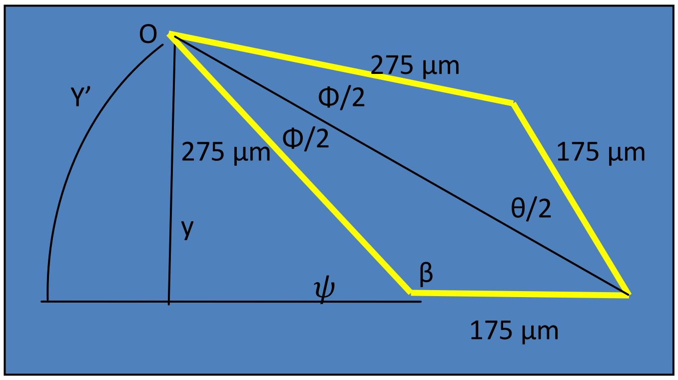


Figure A4. Calculations of vertical displacement y and arc length y’.

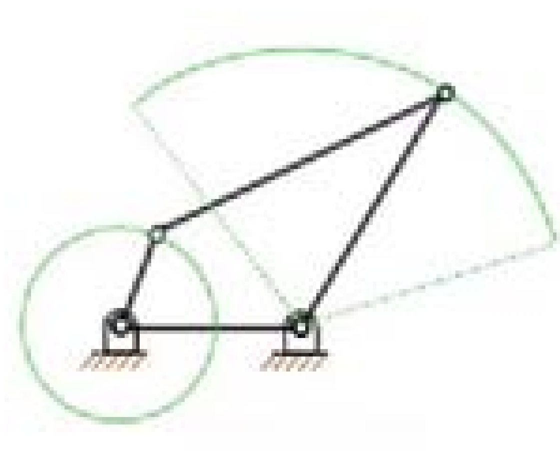


Figure A5. Crank rocker mechanism. The green lines depict the motion of the gear and rocker arm.

The following equations are used to find the vertical displacement y and arc length y’ of the crank rocker mechanism:

$$\beta = 180 - \frac{\theta}{2} - \frac{\Phi}{2} \tag{3}$$

$$\psi = 180 - \beta \tag{4}$$

$$\psi = \frac{\theta}{2} + \frac{\Phi}{2} \tag{5}$$

And with the laws of sine:

$$\frac{275}{sin\left(\frac{\theta}{2}\right)} = \frac{175}{sin\left(\frac{\Phi}{2}\right)} \tag{6}$$

Simplifying the previous equation:

$$\theta = 2asin\left(1.5714sin\left(\frac{\Phi}{2}\right)\right) \tag{7}$$

Combining equations (5) and (7) together, and using ψ as the rotation of the L linkage by an oscillating arm attached to a gear, the displacement y and the arc length y' can be found. The displacement y is found by using equation (8)

$$y = Lsin(\psi) \tag{8}$$

and the arc length y' is found by equation (9) where ψ is in radians.

$$y' = L\psi \tag{9}$$

This gives the displacement of the curved lazy tong for one four bar linkage. Four linkages are implemented in our design. They are in series and move the same distance simultaneously so the arc length displacement for the whole curved lazy tong is calculated by using equation (10)

$$y'_n = L\psi n \tag{10}$$

Where n is the number of linkages in series, which in the Curved Lazy Tong, is 4. The maximum angle ψ goes through when the oscillating arm gear does a full rotation is 87° or 1.518 rads. Using equation (10) the maximum arc length the Curved Lazy Tong extends is approximately

$$y'_n = (275)(1.518)(4) = 1669.8\mu m \ or \ 1.67mm$$

APPENDIX B: AutoCAD Figures

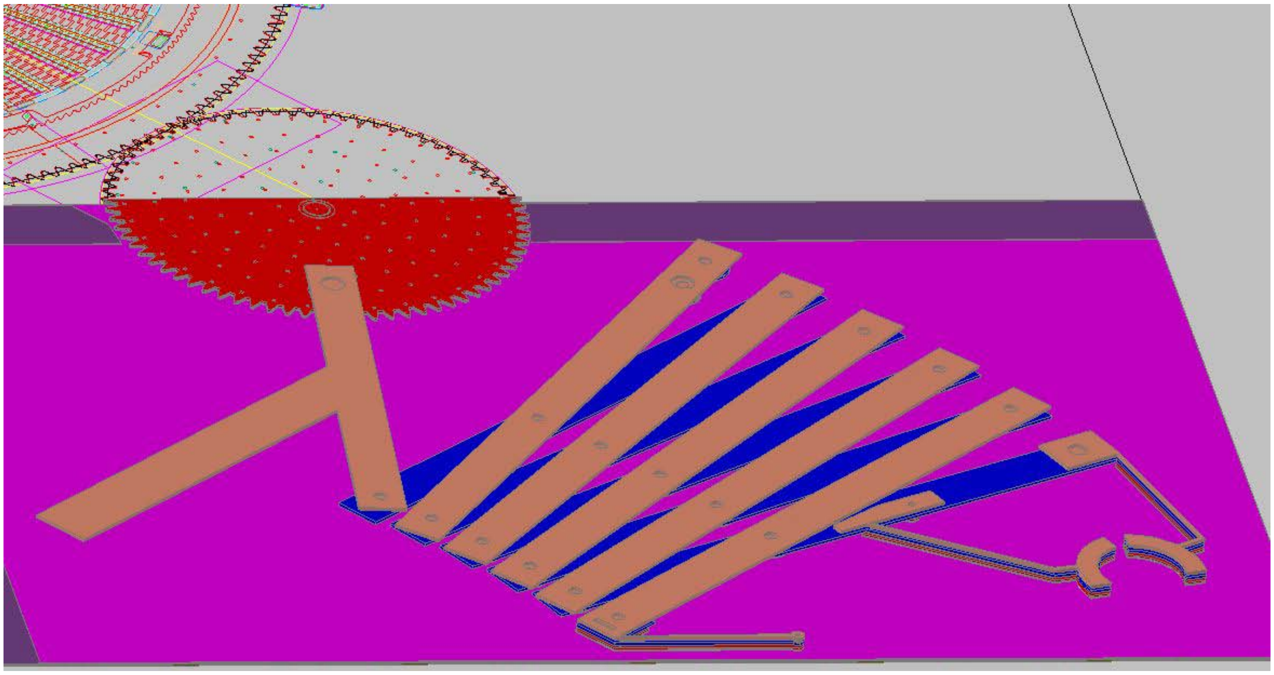


Figure B1. Microgripper 3D AutoCAD model with lazy tongs attached to a crank rocker driven by a TRA.

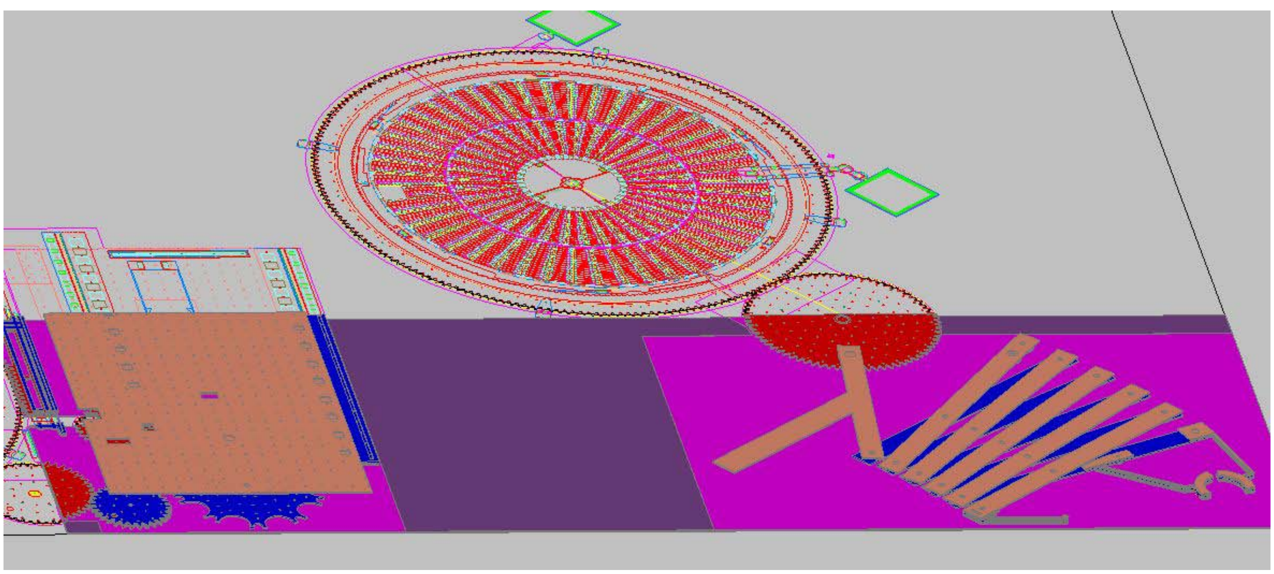


Figure B2. 3D AutoCAD model of lazy tong microgripper and microsaw in as-fabricated position.

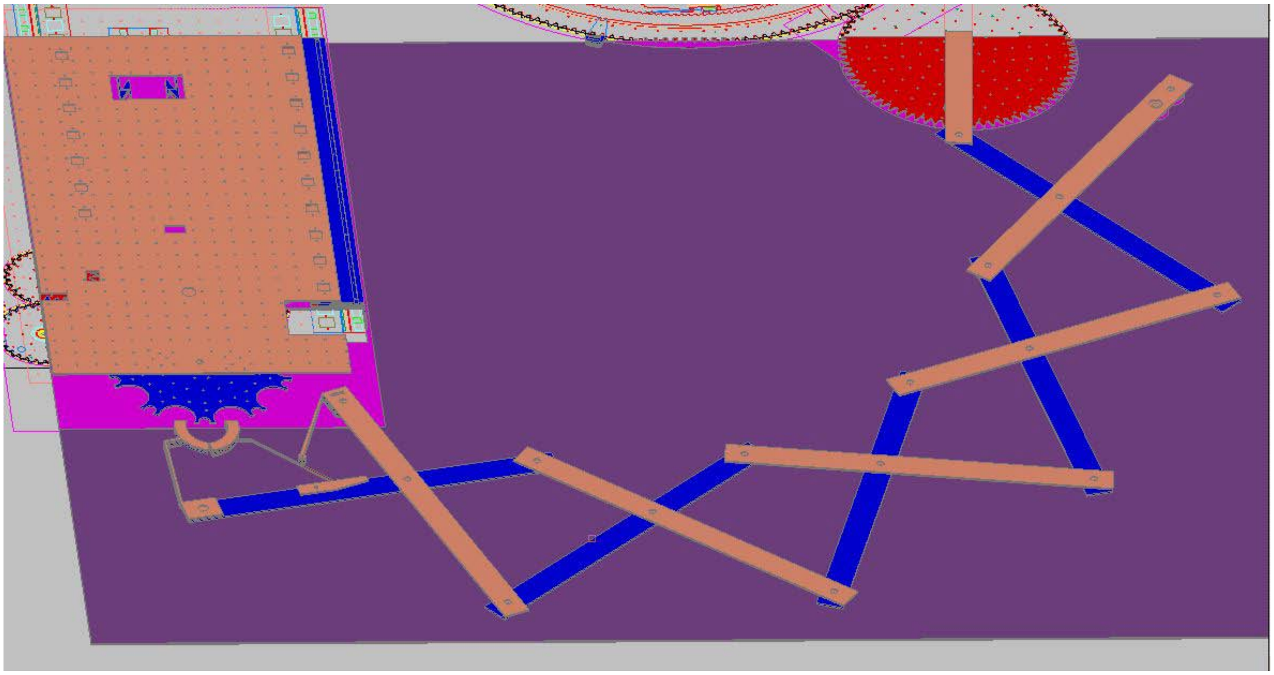


Figure B3. 3D AutoCAD model of lazy tong microgripper in fully extended position in front of microsaw.

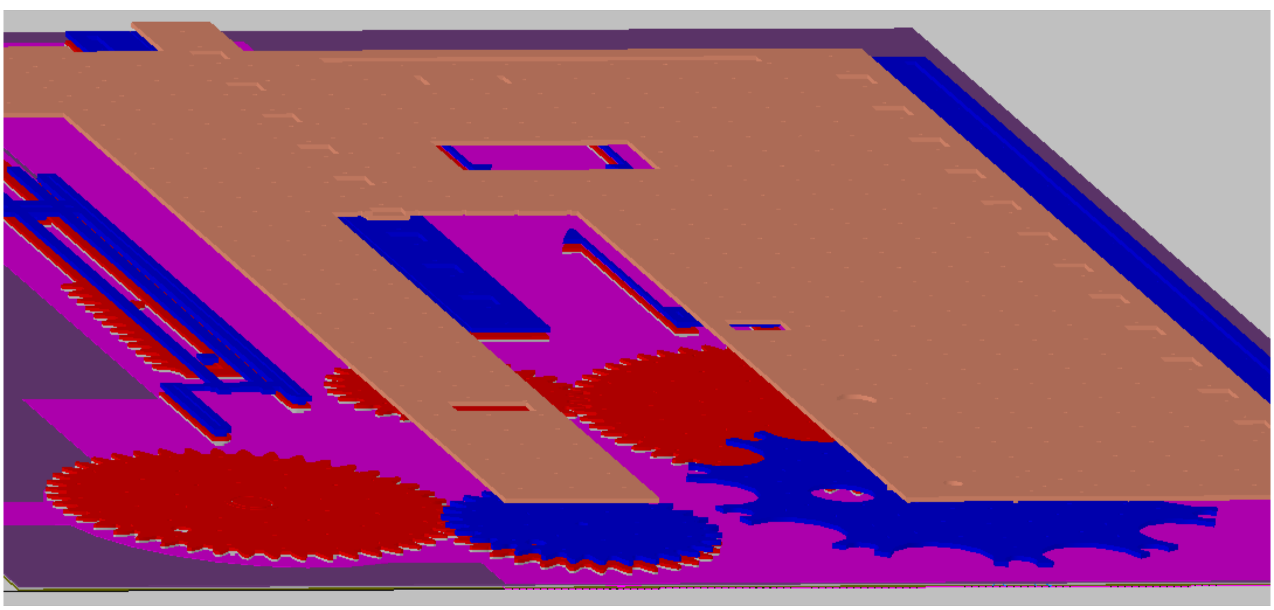


Figure B4. Microsaw with top portion of slider cut out to show inner gear train and latching mechanism.

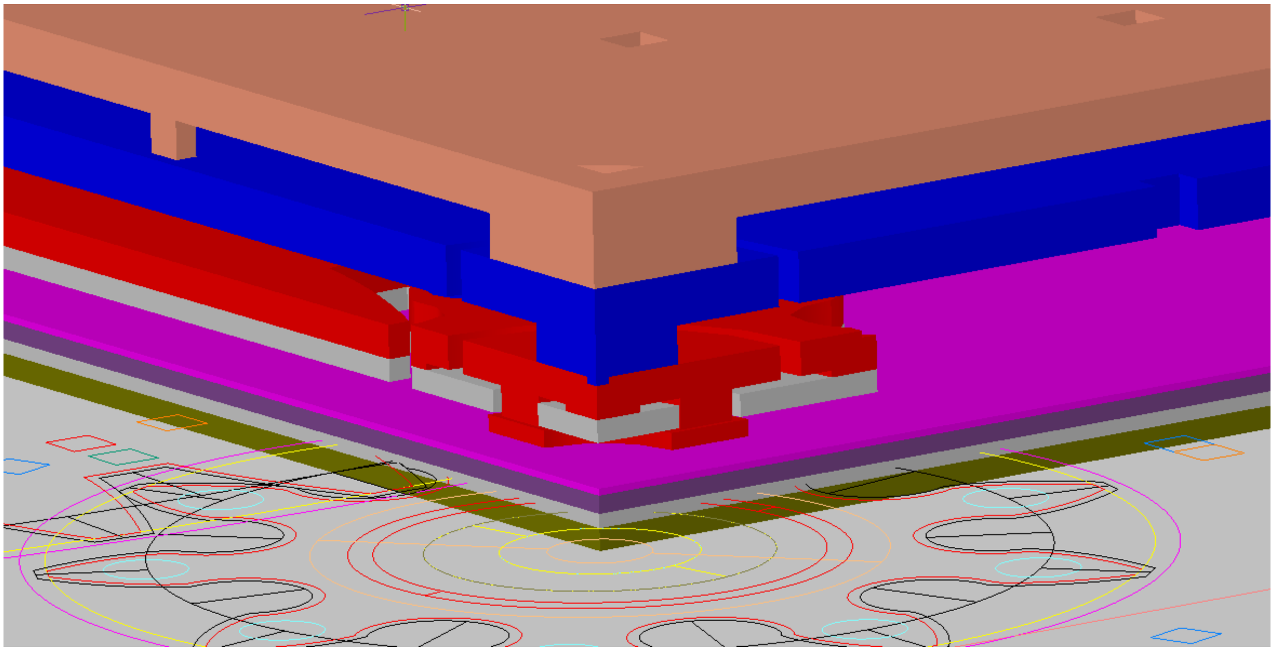


Figure B5: 3D AutoCAD model of suspended moveable gear hub.

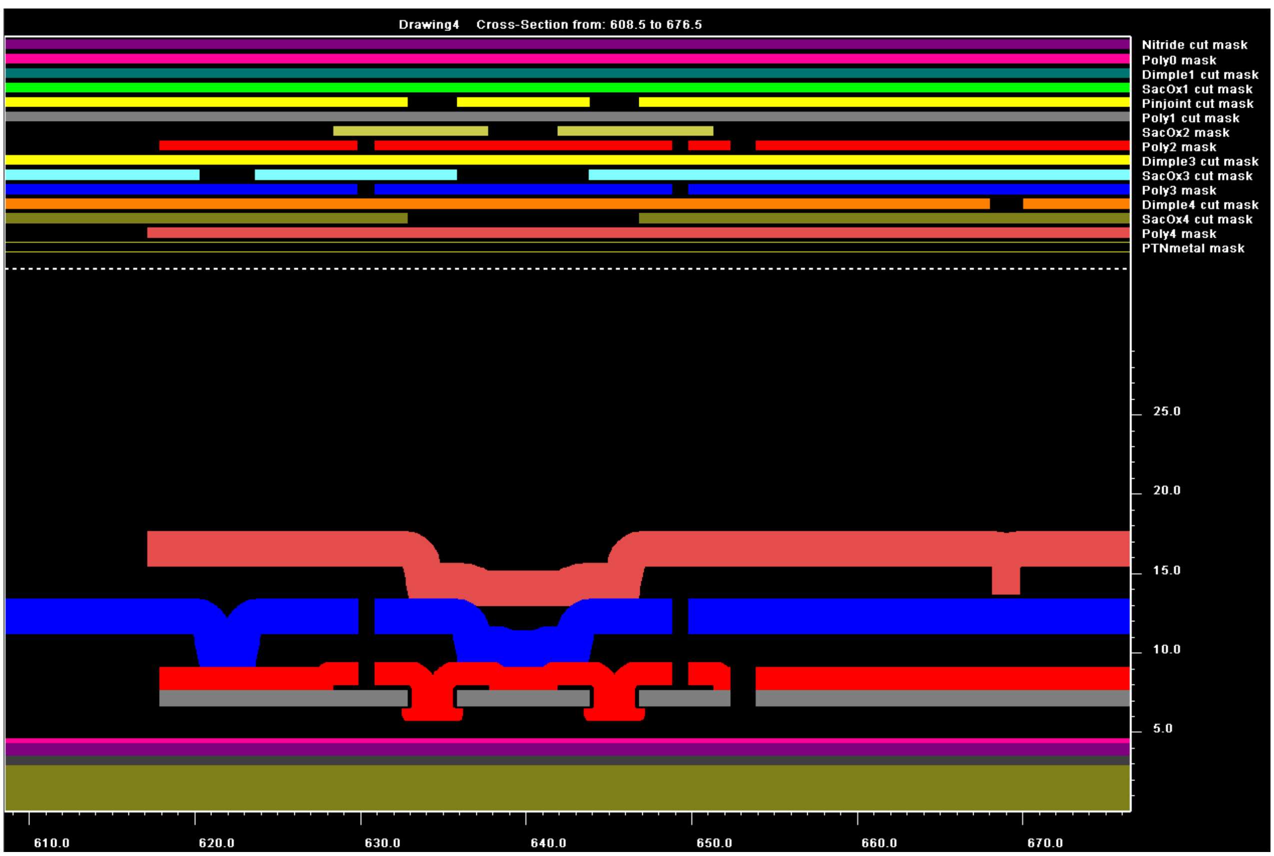


Figure B6: Cross-section model of suspended moveable gear hub.

APPENDIX C: SolidWorks Models

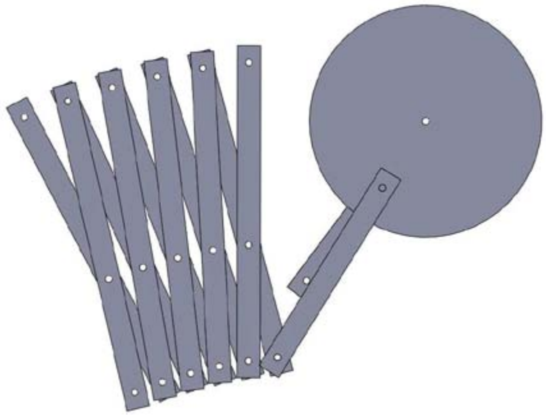


Figure C1. SolidWorks animation of curved lazy tong in original position.

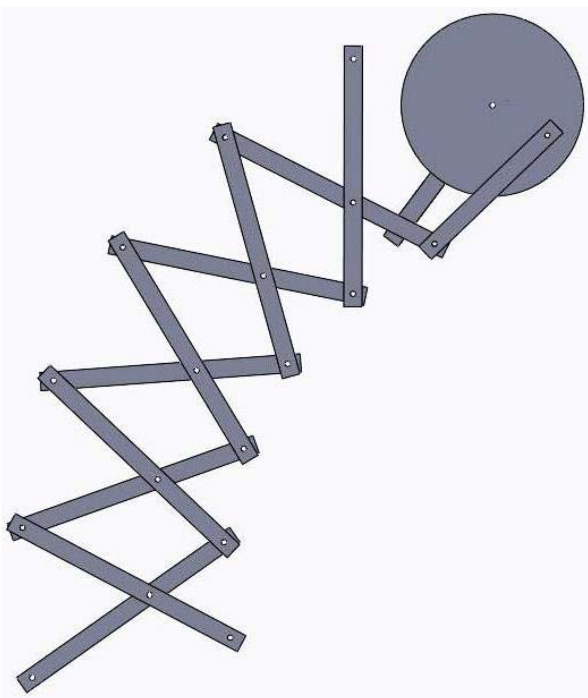


Figure C2. SolidWorks animation of curved lazy tong at half-way extended position.

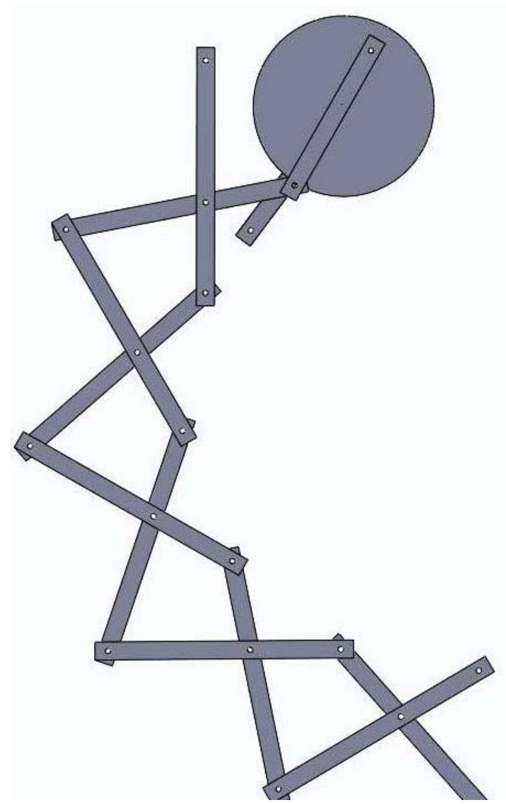


Figure C3. SolidWorks animation of curved lazy tong at full extended position.

APPENDIX D: Figures

Figure D1. Lazy tong paper model contracted.

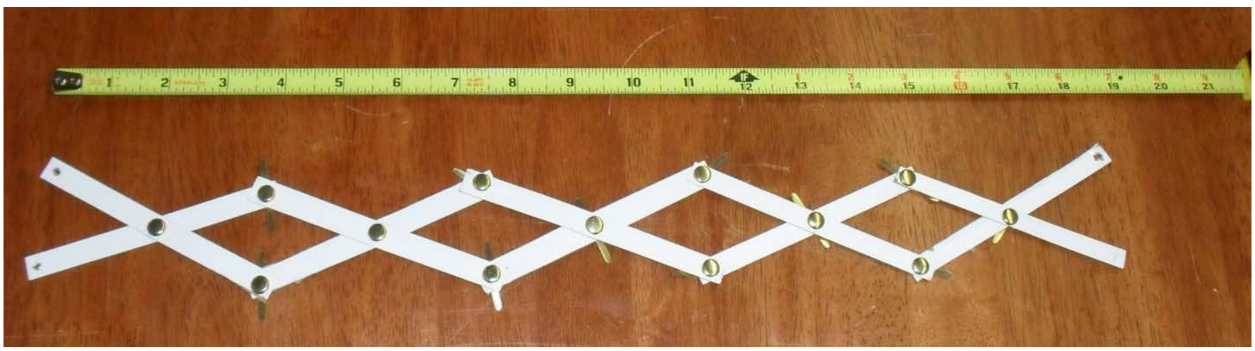


Figure D2. Lazy tong paper model extended.

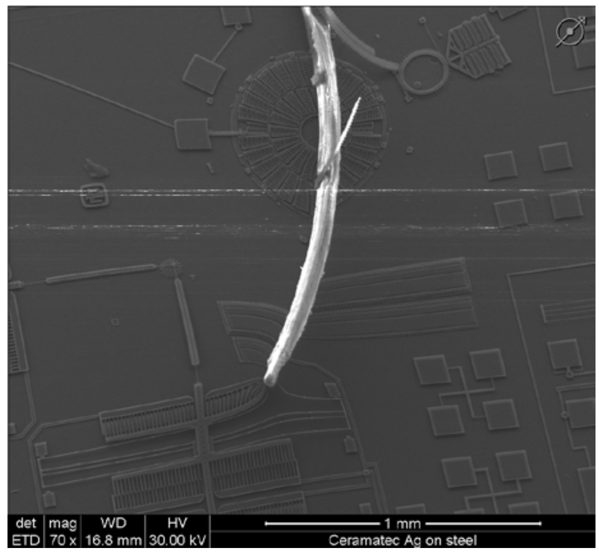
APPENDIX E: Notes and References

Notes and References

[1] Electrostatic torsional ratcheting actuator from the Sandia SUMMiT V™ MEMS standard component library.

[2] The University of Utah is a formal collaborator in the phase-II NSF CCLI proposal submitted spring, 2010 by Dr. Tim Dallas at Texas Tech. This collaboration will supply the University of Utah with packaged devices and a small, portable system comprising power supply / switch box, and a digital microscope with display.

[3] Our experience giving in-lab demonstrations to grade 7-12 Science Olympiad students includes the popular placement of a hair onto a MEMS chip, prior to placement in the SEM. “The nose-hair-from-hell” episode results when the teacher donates the hair, it charges extensively in the SEM, and the resulting dynamic SEM image distortion which appears like warped-space, is always highly engaging for the students.



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